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EIT line shape in an open and partially closed multilevel V-type system

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ABSTRACT

A detail theoretical analysis based on density matrix formulation is carried out to study the electromagnetically induced transparency in a multilevel open V-type system. The density matrix equations are solved numerically for both the Doppler-free and Doppler-broadened medium. We get two coherent electromagnetically induced transparency (EIT) peaks of sub-natural line width and five saturation peaks of sub-Doppler line width. The effect of decoherence on the EIT peak is studied using the theoretical model. A comparative study of the EIT line shape for open and closed V-type system has been done using the theoretical results. In our experiment, we have observed one EIT peak and four saturation peaks in an open V-type system corresponding to the D_2 transition of ^{85}Rb atoms and the EIT peak gets enhanced for partially closed V-type system compared to the open system. The dependence of height and width of the EIT line shape for different pump power values is also observed. The experimental observations are simulated numerically with a good agreement. We have also reported a noticeable change in the contrast of the EIT resonance due to the tuning of the pump laser frequency over the entire probe Doppler profile.

1. Introduction

Over the past few years, the studies of atomic coherence and interference have attracted great interests in the field of quantum optics. These effects are induced due to the atom-laser interaction and lead to interesting modifications of the optical properties of an atomic medium producing a variety of nonlinear resonances such as electromagnetically induced transparency (EIT) [1–12], electromagnetically induced absorption (EIA) [13–18], coherent population trapping (CPT) [19], lasing without inversion (LWI) [20–23], enhancement of refractive index of the absorbing medium [24] etc. The first demonstration of the atomic coherence effect was based on Lambda (Λ) type EIT [1,2]. In Λ-scheme the EIT can be explained using the idea of the coherent population trapping (CPT) of atoms in the ground hyperfine levels [25–27]. The study of V-type EIT has a special interest since it can be described by coherence effect induced by quantum interference only and no population trapping is involved here [28]. In the V configuration, both the pump and probe beams share the same ground level and connect different excited levels. EIT is obtained when the frequency difference between the pump and probe laser matches with the energy separation of the excited levels. In a V-type system, the EIT peak can be characterized as hole burning due to the coherence effects induced by the stronger pump field. Apart from the coherent hole burning effect, the pump beam also produces saturated absorption holes in the ground state population distribution and due to these saturating holes, the velocity selective resonance (VSR) peaks are obtained in the probe transmission profile. Since EIT is the coherent hole burning phenomenon, therefore it has much narrower line width than the VSR peaks caused by the saturation effect due to the pump laser.

The EIT under V-type configuration have been done by several authors [29–34] so far. The demonstration of the V-type EIT for basically a three level system is carried out theoretically by many researchers to understand the system excitation process thoroughly. Lee and Scully [31] had revealed the physics behind EIT and LWI for such scheme based on the concept of dressed states. McGloin [32] had shown that the inclusion of the two photon inhibition results in a number of coherent effects. A population inversion on optical transition is found in a laser driven V-type system due to the coherence effects induced by spontaneous emission [33]. Welch et al. [29] had studied the three level V-type system in the presence of Na atomic beam which is helpful to gather knowledge about the mechanism of a homogeneously broadened system. But the real atomic or molecular system is generally open and multilevel in nature and it is possible to have many nonlinear resonances including EIT and VSR peaks in these systems. The resonance line shape for the open transition will differ significantly than the

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shape of the closed transition and the line shape also depends on the experimental parameters like pump powers and detunings.

In this paper, we present a detail theoretical analysis of the coherent and saturating hole burning processes in a five level open V-type system producing the EIT and VSR resonances. The theoretical model can be well applied to explore the behaviour of any real multilevel atomic system. The density matrix equations corresponding to the level scheme of the ^{85}Rb-D$_2$ transition are solved numerically that includes all orders of pump and probe powers. This method is advantageous to study the nonlinear behaviour of the system because it leads to the solutions without any assumptions. We have solved the Bloch equations numerically both for the Doppler-free and Doppler broadened systems. We get two EIT peaks and five VSR peaks in the simulated Doppler broadened probe transmission profile. We have utilized this theoretical formulation to describe the effect of decoherence on the EIT line shape in V-type system. Simulated probe transmission profiles corresponding to the open and closed V-type systems are also shown. We have done the experiment with rubidium atomic vapour with its natural abundance. We could resolve only one EIT peak and four broadened VSR peaks in our experimental observation. We could not resolve the second EIT peak experimentally that is obtained in the simulated spectrum and we have explained the reason behind this. The effect of tuning of the pump laser frequency over the probe Doppler profile has also been investigated experimentally and it is seen that it has a significant effect on the contrast of the EIT line shape. We have observed the probe transmission profile for a partially closed V-type system modifying the open multilevel structure by applying a repumping laser. The observation corresponding to a partially closed V-type system has been simulated numerically with a good agreement. We have also studied the variation of the EIT width and height for different pump power values. In this paper our main objective is to study the importance of the consideration of all five levels in an open V-type system and their effects on the EIT line shape and also to study the influence of the repumping laser which results in better-parameter EIT resonance with larger amplitude.

2. Theoretical model and analysis

In a basic three level V-scheme, one ground level is connected via two electromagnetic fields called pump and probe with the two different excited levels. But the real system corresponding to the rubidium atomic vapour contains several hyperfine levels which can't be described by the idealized three level model. The hyperfine structure for D$_2$ transition of ^{85}Rb involves six levels. Two of them are the ground levels with $F_g = 2, 3$ and the remaining four are the excited levels with $F_e = 1, 2, 3, 4$. Transitions from the ground levels to the upper levels are governed by the selection rule $\Delta F = 0, \pm 1$. To study the EIT in a V-type system both the probe and pump lasers are applied from $F_g = 2$ to possible F_e's. The level $F_e = 4$ is forbidden to be connected with the $F_g = 2$ since it would violate the selection rule. So, the six level system may be considered as five level system in the presence of the laser beams.

The hypothetical five level system is shown explicitly in Fig. 1. The levels are denoted by $|i\rangle$ where 'i' = 1, 2, 3, 4, 5. The energy separations between $|5\rangle$ and $|4\rangle$ is d_3 ($\sim 2\pi \times 63.4$ MHz), $|4\rangle$ and $|3\rangle$ is d_2 ($\sim 2\pi \times 29.27$ MHz) and that of $|2\rangle$ and $|1\rangle$ is d_1 ($\sim 2\pi \times 3.0357$ GHz). The applied co-propagating pump and probe beams are linearly polarized with electric field E_x = Re [E_{ox} exp $(-i\omega_x t)$] (where $x = c$ for 'pump' and $x = p$ for 'probe'). E_{ox} is the electric field amplitude and ω_x is the corresponding frequency of the laser beam. Both of the lasers are applied from level $|1\rangle$ and connected to the levels $|3\rangle$, $|4\rangle$ and $|5\rangle$. We define the Rabi frequencies for the pump laser as, $\Omega_c = \mu_{i1} E_{oc}/\hbar$ and for probe, $\Omega_p = \mu_{i1} E_{op}/\hbar$ (i = 3, 4, 5). The detunings of the pump and probe fields are denoted

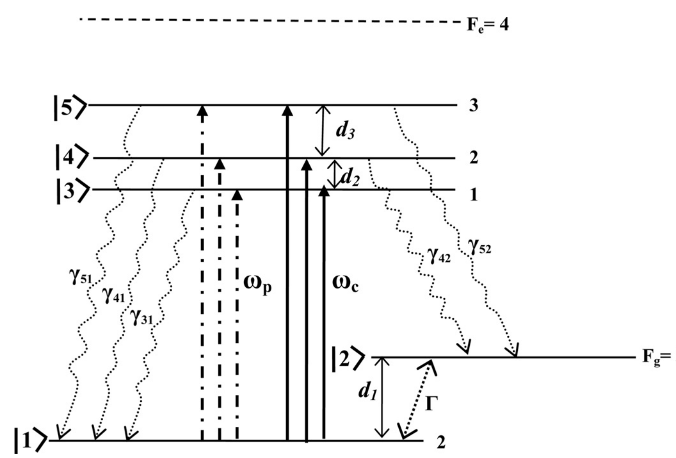

Fig. 1. Energy level diagram of an open five level V-type atomic system corresponding to the hyperfine structure for the D$_2$ transition of ^{85}Rb atoms. The levels are denoted as $|i\rangle$ where 'i' runs from '1' to '5'. The curved dotted lines indicate the excited state radiative decays; 'Γ' is the ground state non-radiative decay rates. The straight dash-dot lines represent the probe laser of frequency ω_p and the solid straight lines indicate the pump laser of frequency ω_c. Both of them are connected between $F_g = 2$ to possible excited states. d_1, d_2 and d_3 are the hyperfine energy splittings.

by $\delta_{i1c} = (\omega_{i1} - \omega_c)$ and $\delta_{i1p} = (\omega_{i1} - \omega_p)$, respectively, with ω_{i1} being the exact frequency between $|1\rangle$ and $|i\rangle$, where 'i' runs from 3 to 5.

The Liouville's equation in terms of the density matrix operator can be expressed as

$$\frac{\partial \rho}{\partial t} = -\frac{i}{\hbar}[H, \rho] + \zeta\rho \qquad \text{(a)}$$

where $H = H_0 + V$ with unperturbed Hamiltonian, $H_0 = \sum_{i=1}^{s} \hbar\omega_{ii} |i\rangle\langle i|$, and the perturbation V (= $-\vec{\mu}.\vec{E}$) arising due to the interaction of the atoms with the laser field is given by$V = -\frac{\hbar}{2}\left[\sum_{i=3}^{5} \Omega_p |\, i\rangle \langle 1\, | e^{-i\omega_p t} + \sum_{i=3}^{5} \Omega_c |\, i\rangle \langle 1\, | e^{-i\omega_c t} + C.C.\right]$

ζ is the phenomenological decay rate included in Eq. (a).

The solutions of Eq. (a) lead us to the population terms as well as the coherence terms that are useful to study the coherent and saturating effects of the system. With the help of the rotating wave approximation (RWA), we are able to deduce the following optical Bloch equations:

$$\begin{aligned}\dot{\rho}_{11} &= -\frac{i}{2}[\Omega_{p31}\left(\tilde{\rho}_{31p} - \tilde{\rho}_{13p}\right) + \Omega_{p41}\left(\tilde{\rho}_{41p} - \tilde{\rho}_{14p}\right) \\ &\quad + \Omega_{p51}\left(\tilde{\rho}_{51p} - \tilde{\rho}_{15p}\right) + \Omega_{c31}\left(\tilde{\rho}_{31c} - \tilde{\rho}_{13c}\right) \\ &\quad + \Omega_{c41}\left(\tilde{\rho}_{41c} - \tilde{\rho}_{14c}\right) + \tilde{\rho}_{c51}\left(\tilde{\rho}_{51c} - \tilde{\rho}_{15c}\right)] \\ &\quad + 2\left(\gamma_{31}\rho_{33} + \gamma_{41}\rho_{44} + \gamma_{51}\rho_{55}\right) - \Gamma_1\rho_{11} + \Gamma_2\rho_{22}\end{aligned}$$

$$\dot{\rho}_{22} = \Gamma_1\rho_{11} - \Gamma_2\rho_{22} + 2\left(\gamma_{42}\rho_{44} + \gamma_{52}\rho_{55}\right)$$

$$\begin{aligned}\dot{\rho}_{33} &= -\frac{i}{2}\left[\left(\Omega_{p31} + \Omega_{c31}\right)\left(\dot{\tilde{\rho}}_{13p} - \dot{\tilde{\rho}}_{31p}\right) + \left(\Omega_{p31} + \Omega_{c31}\right)\right. \\ &\quad \left.\left(\dot{\tilde{\rho}}_{13c} - \dot{\tilde{\rho}}_{31c}\right)\right] - 2\gamma_{31}\rho_{33}\end{aligned}$$

$$\begin{aligned}\dot{\rho}_{44} &= -\frac{i}{2}\left[\left(\Omega_{p41} + \Omega_{c41}\right)\left(\tilde{\rho}_{14p} - \tilde{\rho}_{41p}\right) + \left(\Omega_{p41} + \Omega_{c41}\right)\right. \\ &\quad \left.\left(\tilde{\rho}_{14c} - \tilde{\rho}_{41c}\right)\right] - 2\left(\gamma_{41} + \gamma_{42}\right)\rho_{44}\end{aligned}$$